Advanced CO₂ Leakage Mitigation using Engineered Biomineralized Sealing Technologies

Project Number: FE0004478

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Developing the Technologies and Infrastructure for CCS
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Presentation Outline

• Motivation & Benefit to the Program (required)
• Benefit to the Program and Project Overview (required)
• Background Information
• Accomplishments to Date
  – Injection strategy development (control and prediction)
  – Large core tests – ambient pressure
  – Large core tests – high pressure
  – Small core tests – high pressure
  – MCDP, permeability and porosity assessments
• Progress Assessment and Summary
Benefit to the Program

Program goals being addressed.

Develop and validate technologies to ensure 99 percent storage permanence.

Project benefits statement.

The Engineered Biomineralization Sealing Technology project supports Storage Program goals by developing a leakage mitigation technology for small aperture leaks that can be delivered via low viscosity solutions. The technology, when successfully demonstrated, will provide an alternative to existing cement-based sealing technologies.
The goal of this project is to develop a biomineralization-based technology for sealing preferential flow pathways in the vicinity of injection wells.

Objective 1) Construct and test mesoscale high pressure rock test system (HPRTS).

Objective 2) Develop biomineralization seal experimental protocol.

Objective 3) Creation of biomineralization seal in different rock types and simulating different field conditions.

Target metrics for technology performance.

1) Demonstrate the ability to control the spatial distribution of the biobarrier on the 1 meter scale.

2) Achieve a 3-4 order of magnitude reduction in permeability and a 10- to 25-fold increase in minimum capillary displacement pressure (MCDP).

3) Develop a barrier growth protocol consistent with field deployment.
• Focus the remaining slides, logically walking through the project. Focus on telling the story of your project and highlighting the key points as described in the Presentation Guidelines.

• When providing graphs or a table of results from testing or systems analyses, also indicate the baseline or targets that need to be met in order to achieve the project and program goals.
Abandoned Well Leakage Mitigation Using Biomineralization


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Center for Biofilm Engineering
Montana State University
Bozeman MT, 59717

Richard Esposito – Southern Company
Rainer Helmig, Holger Class, Johannes Hommel – University of Stuttgart
Peter Walsh – University of Alabama-Birmingham
Concept/Motivation
Cement is a good technology for large aperture leaks, but is sometimes considered too viscous to plug small aperture leaks such as small fractures or interfacial delaminations.

In some problematic cases it may be desirable to plug the rock formation around the well.

A missing tool is a plugging technology that can be delivered via low-viscosity fluids.
Urea hydrolysis increases alkalinity and thus the saturation state of many minerals (e.g. calcium carbonate)

\[
\text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O} \rightarrow \text{NH}_2\text{COOH} + \text{NH}_3 \\
\text{NH}_2\text{COOH} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{H}_2\text{CO}_3 \\
\text{CO}(\text{NH}_2)_2 + 2 \text{H}_2\text{O} \rightarrow 2 \text{NH}_3 + \text{H}_2\text{CO}_3 \quad \text{(Urea hydrolysis)}
\]

\[
2\text{NH}_3 + 2\text{H}_2\text{O} \leftrightarrow 2\text{NH}_4^+ + 2\text{OH}^- \quad \text{(pH increase)}
\]

\[
\text{H}_2\text{CO}_3 + 2\text{OH}^- \leftrightarrow \text{HCO}_3^- + \text{H}_2\text{O} + \text{OH}^- \leftrightarrow \text{CO}_3^{2-} + 2 \text{H}_2\text{O}
\]

\[
\text{CO}_3^{2-} + \text{Ca}^{2+} \leftrightarrow \text{CaCO}_3 \quad \text{(carbonate precipitation)}
\]

\[
\text{CO}(\text{NH}_2)_2 + \text{Ca}^{2+} + 2\text{H}_2\text{O} \leftrightarrow 2\text{NH}_4^+ + \text{CaCO}_3
\]

Accomplishments to Date

- Demonstrated ability to control mineralization distribution
- Developed computational tools to simulate mineral distribution
- Successful collection of large diameter cores
- Demonstrated ability to seal fractures under ambient pressure using the biomineralization approach
- Designed and constructed a high pressure vessel for large diameter core experiments
- Performed high pressure sealing experiment on large diameter core and sandpack
- Continuing to perform small and meso-scale experiments to better understand and control distribution of biomineral seals
Darcy-scale model

Objective 2) Develop biomineralization seal experimental protocol.

Calibration (columns 1 & 2)

Predict future experiments and injection strategies

Ebigbo, A; Phillips, A; Gerlach, R; Helmig, R; Cunningham, AB; Class, H; Spangler, LH. Darcy-scale modeling of microbially induced carbonate mineral precipitation in sand columns. Water Resour. Res. 2012, 48 (7), W07519.
**Injection strategy development**

**Objective 2)** Develop biomineralization seal experimental protocol.

- **Promote homogeneous distribution**
  - Urea
  - No urea or Ca$^{2+}$
  - Urea & Ca$^{2+}$
  - No urea or Ca$^{2+}$
  - 1) Promote biofilm growth
  - 2) Resuscitation
  - Lower saturation state to reduce instantaneous precipitation
  - Fast Injection ($Da <<1$)
  - 1) Displacement
  - 2) Biomineralization (~4 hours)

- **Prevent near-injection-point plugging**

- **Promote efficient precipitation**

- **Manipulating saturation state**

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Ebigbo, A; Phillips, A; Gerlach, R; Helmig, R; Cunningham, AB; Class, H; Spangler, LH. Darcy-scale modeling of microbially induced carbonate mineral precipitation in sand columns. Water Resour. Res. 2012, 48 (7), W07519.
Large Sample Procurement

Objective 1) Construct and test mesoscale high pressure rock test system (HPRTS).

Objective 2) Develop biomineralization seal experimental protocol.

\[ K = Q \frac{\ln\left(\frac{r_0}{r_w}\right)}{\frac{\text{fracture length}}{\text{core circumference}}} \frac{2\pi \Delta p b_1}{2\pi} \]

\[ K = Q \frac{\ln\left(\frac{r_0}{r_w}\right)}{2\pi \Delta p b_2} \]

Permeability (mD) vs. Experiment Duration (days)

Radial flow rather than fracture-dominated flow was observed.

Meso-Scale High Pressure Vessel

Objective 1) Construct and test mesoscale high pressure rock test system (HPRTS).
High Pressure Experiments with Large Cores

Objective 1) Construct and test mesoscale high pressure rock test system.
Objective 2) Develop biomineralization seal experimental protocol.
Objective 3) Creation of biomineralization seal in different rock types …

Graph: Permeability (mD) vs Time (days)

30 in x 15 in sandstone core: high pressure experiment
Axial flow high pressure core testing system

Objective 2) Develop biomineralization seal experimental protocol.
Objective 3) Creation of biomineralization seal in different rock types …

• Specifications:
  – Hassler-type core holder
  – 1” diameter cores
  – Up to 6” length
  – Axial flow
  – 2000 psi, 60°C
  – Constant pressure/constant flow rate operation (ISCO pumps)
  – Data Acquisition
    • $\Delta p$
    • flow rate
    • pH
    • conductivity
Axial flow ~76 bar (1100 psi)

Objective 2) Develop biomineralization seal experimental protocol.
Objective 3) Creation of biomineralization seal in different rock types …
Axial flow ~76 bar (1100 psi)

- 2.4 mD Biomineralized core, whole
- 1.4 mD
- 1.9 mD

- 8.1 ± 2.4 mD 45 mg/g Ca
- 3.6 ± 0.5 mD 50 mg/g Ca
- 30 mD
- 29 mD 2 mg/g Ca Quartz only
- 30.4 mD 1 mg/g Ca Quartz only

Direction of flow

Biomineralized Core, cut in half with “skin” on

Influent skin 88 mg/g Ca
Influent without skin
Effluent skin 76 mg/g Ca
Effluent without skin

Control core, whole
Control core, cut in half

Quartz only
Pore (Throat) Size Distribution

- Reduction in overall porosity by 24%
- Porosity decreased more on effluent end than influent end
- Pore (throat) size distribution changed

<table>
<thead>
<tr>
<th>Pore volume diameter</th>
<th>Control average</th>
<th>Biomin Influent Average</th>
<th>Biomin Effluent Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 1 µm</td>
<td>15%</td>
<td>22%</td>
<td>28%</td>
</tr>
<tr>
<td>1-10 µm</td>
<td>33%</td>
<td>26%</td>
<td>38%</td>
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<tr>
<td>10-100 µm</td>
<td>42%</td>
<td>29%</td>
<td>22%</td>
</tr>
<tr>
<td>100-1000 µm</td>
<td>10%</td>
<td>23%</td>
<td>13%</td>
</tr>
<tr>
<td>6-16 µm</td>
<td>51%</td>
<td>33%</td>
<td>31%</td>
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</table>
Core is initially saturated with brine. ScCO$_2$ is forced through under pressure until pressure difference stabilizes. $\Delta P$ is MCDP (Hildebrand et al. 2002)

- MCDP is the minimum pressure across the length of a brine-saturated rock core which results in ScCO$_2$ breakthrough.
- MCDP can the thought of as a measure of the resistance to ScCO$_2$ penetrating through cap rock.

## Summary Table with permeability, porosity and MCDP results

<table>
<thead>
<tr>
<th>Exp. #</th>
<th>Perm. initially (mD)</th>
<th>Perm. before sent to UAB (mD)</th>
<th>Porosity</th>
<th>Perm. with N$_2$ (mD)</th>
<th>MCDP (bar)</th>
<th>24 hr scCO$_2$?</th>
<th>Perm. w/ N$_2$ after scCO$_2$ (mD)</th>
<th>MCDP after scCO$_2$ (bar)</th>
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<tbody>
<tr>
<td>1</td>
<td>37</td>
<td>0.2</td>
<td>14.7%</td>
<td>NM</td>
<td>NM</td>
<td>No</td>
<td>NM</td>
<td>NM</td>
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<td>2</td>
<td>37.6</td>
<td>0.2</td>
<td>NM</td>
<td>5.9±3.1</td>
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<td>Yes</td>
<td>4.27±0.1</td>
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<td>3</td>
<td>34</td>
<td>0.02</td>
<td>14.5%</td>
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<td>Control</td>
<td>27</td>
<td>27</td>
<td>19.2%</td>
<td>71.6±0.8</td>
<td>0.007</td>
<td>No</td>
<td>NM</td>
<td>NM</td>
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</table>
High Pressure Sandpack Experiment
High Pressure Sandpack Experiment

Significant ppt on the bottom stainless ring on the outside of the sand pack.
Goal: Develop a biomineralization-based technology

Objective 1) Construct and test mesoscale high pressure rock test system (HPRTS). – completed

Objective 2) Develop biomineralization seal experimental protocol. – achieved for 1-D (axial) and 2-D (radial) systems, in progress for quasi-3D system (radial flow meso-scale system)

Objective 3) Creation of biomineralization seal in different rock types and simulating different field conditions. – achieved for sandstone, (unconsolidated) sandpacks, in progress for fractured cement, cement-steel interfaces, cement-sandstone interfaces
Progress

Target metrics for technology performance.

1) Demonstrate the ability to control the spatial distribution of the biobarrier on the 1 meter scale. – achieved (large core diameter experiments)

2) Achieve a 3-4 order of magnitude reduction in permeability and a 10 to 25 fold increase in minimum capillary displacement pressure (MCDP). – achieved in fractured sandstone core, in 1 in diameter sandstone cores

3) Develop a barrier growth protocol consistent with field deployment – in progress – see next presentation for more detail
Goal: Develop a biomineralization-based technology for well sealing

Workplan generally on track

but: it has been challenging to procure large diameter rock cores of suitable permeability (i.e. 50 mD and above) which can be used to run radial flow experiments in the meso-scale high pressure vessel
Summary

- Biofilm formation and biomineralization shows promise as a method to seal small aperture leaks in the subsurface.
- Other mineralogy, porosity, permeability cores will be run.
- Thought must be given to downhole delivery of fluids for sealing technology.
- In-Well demonstration is being pursued (next presentation).
Appendix

– These slides will not be discussed during the presentation, but are mandatory
# Gantt Chart

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
<th>Q6</th>
<th>Q7</th>
<th>Q8</th>
<th>Q9</th>
<th>Q10</th>
<th>Q11</th>
<th>Q12</th>
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<tr>
<td>1</td>
<td>Project Management &amp; Planning</td>
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<td>2</td>
<td>Construction of high pressure rock testing systems (HPRTS)</td>
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<td>2.1</td>
<td>Design and fabricate HPRTS system</td>
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<td>2.2</td>
<td>Initial testing of HPRTS</td>
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<td>2.3</td>
<td>Characterizing the initial flow properties of rock samples</td>
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<td>3</td>
<td>Develop biomineralization seal experimental protocol</td>
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<td>3.1</td>
<td>Radial Flow</td>
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<td>Axial (Linear) Flow</td>
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<td>Assessment of effectiveness of biomineralization seal</td>
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<td>4</td>
<td>Creation of biomineralization seal in different rock types</td>
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<td>ScCO2 challenges of mineralized rock</td>
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<td>5</td>
<td>Experimental Simulation Modeling of Processes</td>
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